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Lab and Bench-Scale Pelletization of Torrefied Wood Chips—Process Optimization and Pellet Quality

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Abstract Combined torrefaction and pelletization is used to increase the fuel value of biomass by increasing its energy density and improving its handling and combustion properties. In the present study, a single-pellet press tool was used to screen for the effects of pellet die temperature, moisture content, additive addition, and the degree of torrefaction on the pelletizing properties and pellet quality, i.e., density, static friction, and pellet strength. Results were compared with pellet production using a bench-scale pelletizer. The results indicate that friction is the key factor when scaling up from single-pellet press to bench-scale pelletizer. Tuning moisture content or increasing the die temperature did not ease the pellet production of torrefied wood chips significantly. The addition of rapeseed oil as a lubricant reduced the static friction by half and stabilized pellet production; however, the pellet quality, strength, and density were negatively affected. The pellets produced from pine wood torrefied at 250 and 280 °C were shorter than pellets produced from untreated wood and their quality did not match conventional wood pellet standards. However, the heating value of the torrefied pellets was higher and the particle size distribution after grinding the pellets was more uniform compared to conventional wood pellets.

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Introduction

Wood pellets are increasingly used as a substitute for coal in combined heat and power plants in Denmark and other European countries [1, 2]. Pelletization of biomass eases handling and reduces transportation and storage costs. Furthermore, fuel pellets from biomass have standardized and uniform properties, quality standards and the pellets are traded globally on an existing and mature market. Recently, focus has been set on combining both pelletization and torrefaction processes, resulting in both commercial interest and increasing research activities [3, 4]. Torrefaction is a mild temperature (200–300 °C) pretreatment process of biomass in an inert atmosphere [5]. During torrefaction, the biomass loses water and a proportion of its volatile content, becoming dry, brittle, and darker in color. Furthermore, torrefied biomass is more hydrophobic, has a higher calorific value and is easier to grind than untreated biomass [6–8]. The properties of pellets made from torrefied biomass are in many ways similar to coal [9, 10]. Several studies have been made to investigate the pelletizing properties of torrefied biomass. Using a standardized single-pellet press method, Stelte et al. [11] and Li et al. [12] showed that the pelletization of torrefied biomass required more energy due to the high friction between the biomass and the surface of the press channel, and the resulting pellets were less stable compared to conventional wood pellets. Tests on the pilot-scale pellet mill have also shown that pelletization of torrefied biomass required higher energy and resulted in lower pellet strength and density compared to untreated biomass [13]. However, more studies are needed to confirm this. Although single-pellet press testing is a widely used method for testing the pelletizing properties of new types of

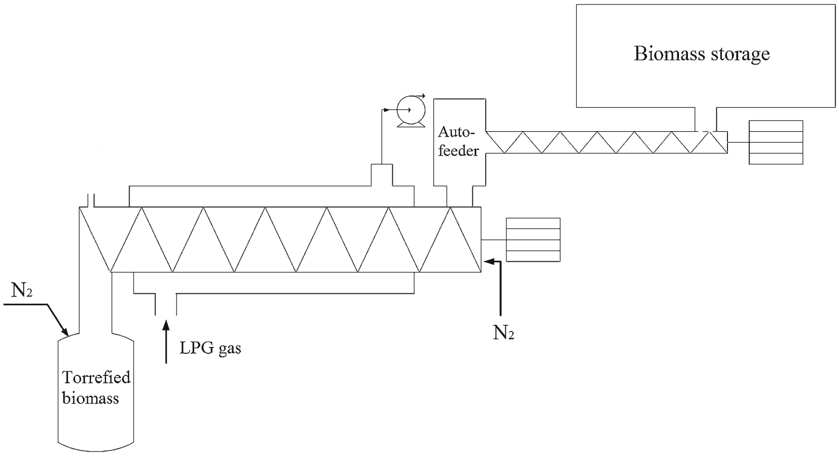

Fig. 1 Illustration of the screw conveyor torrefaction reactor and feeding system built in DTU Risø campus, Denmark

biomass, there is lack of studies testing the scale up of single-pellet press test results with bench and pilot-scale pelletizers. The effects of die temperature, pressure, moisture content, biomass species and additives can be quickly screened in the single-pellet press before scaling up the trials. However, one important drawback is that the pellets produced in this way are not the same as those from the pilot-scale pelletizer [9, 10]. Major differences are that pellets in a single-pellet tool are not produced continuously and the flow of biomass into the openings of the press channels cannot be simulated exactly as it is in a real pellet press. Therefore, it is difficult to foresee the quality of the final products from large-scale pelletizer by using single-pellet press. On the other hand, using pilot-scale pelletizer to study the effects of different parameters is time and material consuming, and some process parameters cannot be easily controlled since they are connected but dependent on each other. For example, die temperature is influenced by the friction and the friction depends on the press channel length [9].

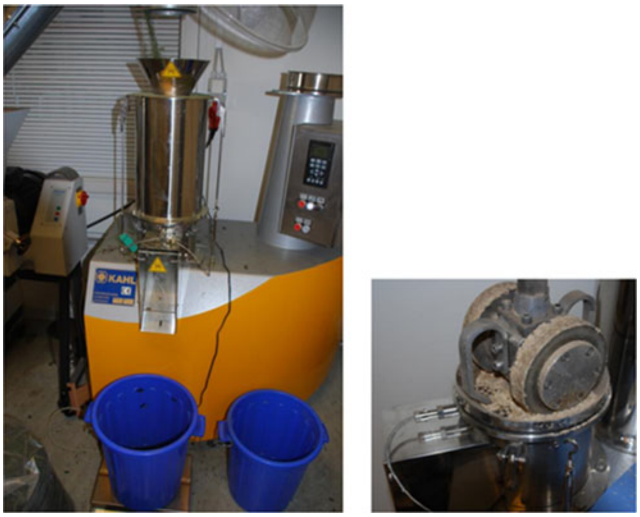

Fig. 2 The KAHL flat die bench-scale pellet press (*left*), flat die and rollers of the bench-scale pellet press (*right*)

In the present work, pelletizing properties of wood chips torrefied at 250 and 280 °C were tested in a single-pellet press. The effects of die temperature, moisture content, additive, and degree of torrefaction on the friction in the press channel of the pellet press, pellet density, and the pellet compression strength were screened to find the optimal conditions. Subsequently, the optimized parameters were used to adjust the settings of a bench-scale pelletizer. The quality of produced pellets, i.e., strength, durability, and density were investigated by standard protocols. Furthermore important fuel properties such as heating value and grindability were determined using a bomb calorimeter and a bench-scale disk mill.

Material and Methods

Materials

Wood chips (*Pinus sylvestris* L.) from Zealand, Denmark (55°30′ N 11°45′ E) were used as raw material. The size of the chips varied from 30×30×20 to 100×100×30 mm. The chips were stored for several months in a shielded container with air circulation and had a moisture content of around 16 % on wet mass basis.

Torrefaction

The torrefaction reactor (Fig. 1) is a screw conveyor reactor with feeding capacity of 6 kg h^{-1}. The reactor is indirectly heated by burning liquefied petroleum gas. A nitrogen flow of 2.5 L min^{-1} was used as a carrier gas in the torrefaction and collecting unit through the test to avoid ignition. The temperature of flue gas is controlled by adjusting the gas and air volume, and the temperature of reaction was monitored by 11 thermocouples located in different places through the reactor. The residence time can be controlled by adjusting the rotating speed of the screw conveyor. Torrefaction was carried out at 250 and 280 °C with residence time of about 1 h.

Single-Pellet Press

The biomass was pelletized using a single-pellet press as described in [9]. The unit consisted of a cylindrical die 8 mm in diameter, made of hardened steel, packed with heating elements and thermal insulation. The temperature was controlled using a thermocouple connected to a control unit. The end of the die was closed using a removable backstop. Force was applied to the press using a universal testing system (AGX, Shimadzu, Japan) and detected using a 200-kN load cell. Data recorded was the compression force and the friction (force that is required to extrude the pellet from the press channel). About 750 mg sample material at a particle size of 1–2 mm was compressed at a rate of 100 mm min^{-1} until a maximum pressure of 300 MPa was reached. The pressure was held for 5 s. Subsequently to compression, the bottom piston was removed from the die, and the pellet was pressed out of the channel at a rate of 100 mm-min^{-1}. The static friction was determined from the force required to extrude the pellet from the die. The static friction is the maximum force required to set the pellet into motion and is closely related to the pelletizing pressure generated in the press channel of a pellet mill [14]. The average value of at least five measurements was determined and a 95 % confidence interval was calculated. Five different die temperatures (125, 155, 160, 165, and 190 °C) and three levels of moisture content of the torrefied wood chips (0.5, 5, and 10 %) were used for pelletizing. Besides, 2 % rapeseed oil was added as a lubricant.

Bench-Scale Pelletizer

A bench-scale flat die pellet press (Model 14–175, Amandus Kahl GmbH & Co. KG, Germany) with a power of 3 kW and a

Table 1 Summary of pelletization test conditions in the single-pellet press and results (95 % confidence intervals of mean values within brackets**)**

Torrefaction temperature (°C)	Moisture content (%)	Rapeseed oil (%)	Die temperature (°C)	Strength (N)		Density (kg m^{-3})		Static friction (N)	
Untreated wood chips	ca. 10	No	125	1,080 (54)	A[a]	1,261 (3)	A	253 (22)	A
			155	1,115 (80)	AB	1,308 (45)	B	226 (17)	A
			160	1,137 (108)	AB	1,275 (8)	AB	233 (9)	A
			165	1,240 (61)	B	1,280 (6)	AB	242 (36)	A
			190	1,132 (71)	AB	1,294 (3)	AB	257 (18)	A
250	5	No	125	737 (37)	A	1,167 (7)	A	923 (46)	A
			155	832 (44)	B	1,203 (3)	B	832 (16)	AB
			160	847 (35)	B	1,206 (2)	B	853 (24)	B
			165	947 (63)	C	1,211 (2)	B	791 (46)	B
			190	987 (51)	C	1,223 (2)	C	912 (41)	AB
280	5	No	125	596 (38)	A	1,101 (4)	A	972 (27)	A
			155	694 (69)	AB	1,149 (5)	BC	975 (12)	BC
			160	579 (68)	A	1,133 (12)	B	1,009 (44)	B
			165	733 (41)	BC	1,157 (3)	C	1,033 (48)	C
			190	874 (55)	C	1,171 (5)	C	934 (39)	BC
250	ca. 5	2	125	265 (29)	A	1,058 (13)	A	523 (33)	A
			190	317 (121)	A	1,145 (20)	B	492 (36)	A
	0.5	No	125	606 (51)	B	1,069 (13)	A	1837 (89)	B
			190	1,033 (59)	C	1,231 (29)	C	879 (51)	C
	10	No	125	614 (71)	B	1,113 (9)	B	828 (27)	C
			190	859 (47)	D	1,219 (14)	C	638 (40)	AC
280	ca. 5	2	125	302 (36)	A	1,062 (17)	A	620 (46)	AE
			190	369 (71)	A	1,122 (15)	B	558 (45)	A
	0.5	No	125	433 (33)	A	1,021 (20)	C	2,132 (102)	B
			190	889 (26)	B	1,164 (3)	D	1,109 (44)	C
	10	No	125	358 (98)	A	1,022 (23)	C	966 (67)	C
			190	483 (190)	A	1,144 (6)	BD	736 (60)	E

For example, the strength of untreated wood chips with die temperature of 125 °C is not significantly different from the strength of untreated wood chips with die temperature of 155°, but significantly different from the strength of untreated wood with die temperature of 165 °C

[a] For each tested torrefaction temperature (first column), the same letter in each column represents mean values not significantly different by one-way ANOVA followed by Tukey's test at the 0.05 level

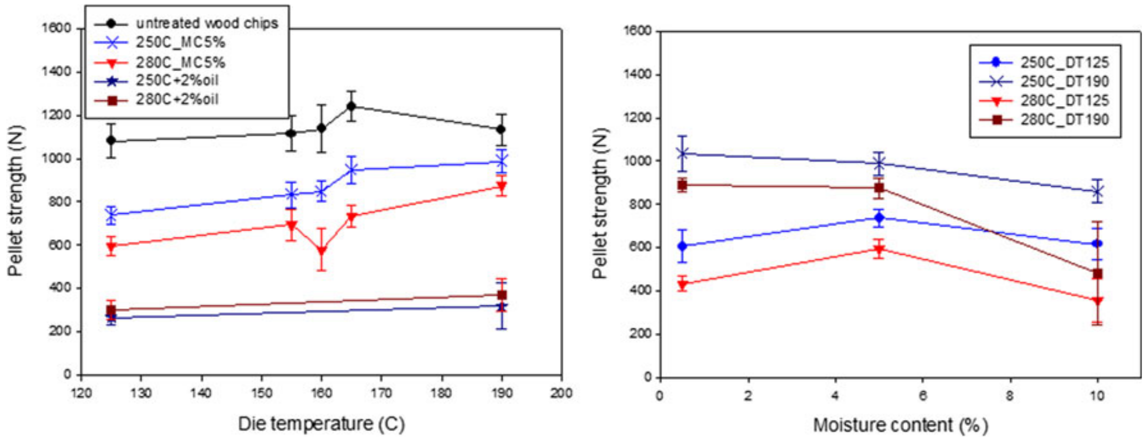

Fig. 3 The strength of pellets prepared at different die temperatures and pellets conditioned with different moisture content (*MC* denotes moisture content and *DT* refers to die temperature)

capacity of 10–50 kg h^{-1} was used to produce torrefied pellets. The produced pellets were used for durability test, heating value measurement and grinding energy determination. The material with a particle size <4 mm was pressed from the top through a horizontally placed die (see Fig. 2). A channel diameter of 6 mm was used. The experiments were run using a pre-warmed die and samples were taken at steady state. The press was equipped with a continuous data logging system logging data of the amount of produced pellets, power consumption, and die temperature.

Characterization of Pellets

Strength and Density

The pellets produced from the single-pellet press were cylindrical, 8 mm in diameter, and about 12 mm in length. The pellets were left to cool overnight, and the pellet strength was determined by crushing the pellet perpendicular to the length of the pellet as described earlier [11, 15]. The pellet was laid down on the side and increasing force was applied until crushing. Prior to this, the length, diameter, and mass were measured for density calculation. Four to ten replicates were made for each sample. The error bars in the plots refer to the standard deviation based on the sample.

Durability Test

The durability of pellets produced in the bench-scale pelletizer was determined according to the EN 15210–1 standard [16], also known as tumbling can test. Prior to the testing, pellets were sieved through a 3.15-mm screen (round holes) to remove fines and dust from the samples. Five hundred grams of dust-free pellets were then loaded into the chamber of the standard durability tester and exposed to 500 rotations within a time interval of 10 min. The amount of fines formed during the test was determined by sieving the treated sample again through the 3.15-mm screen and determination of the weight

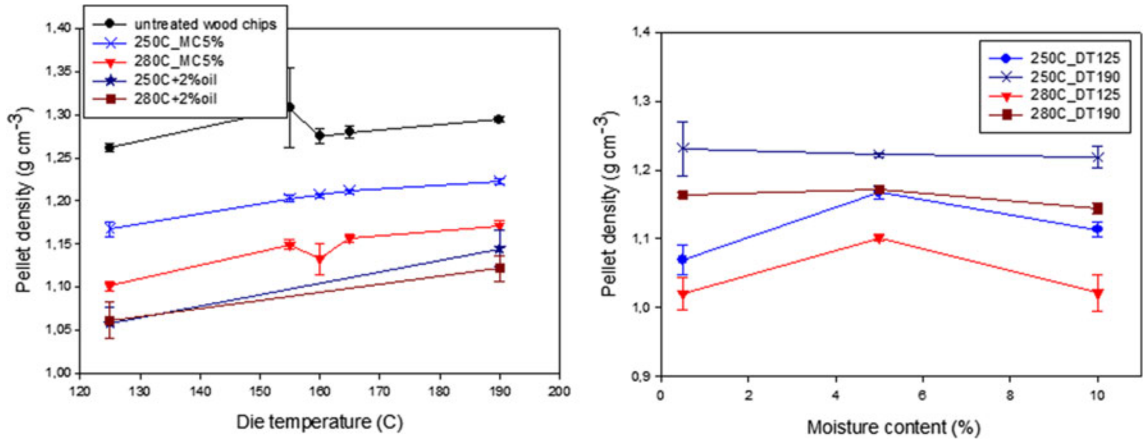

Fig. 4 The density of pellets prepared at different die temperatures and pellets with different moisture contents (*MC* denotes moisture content and *DT* refers to die temperature)

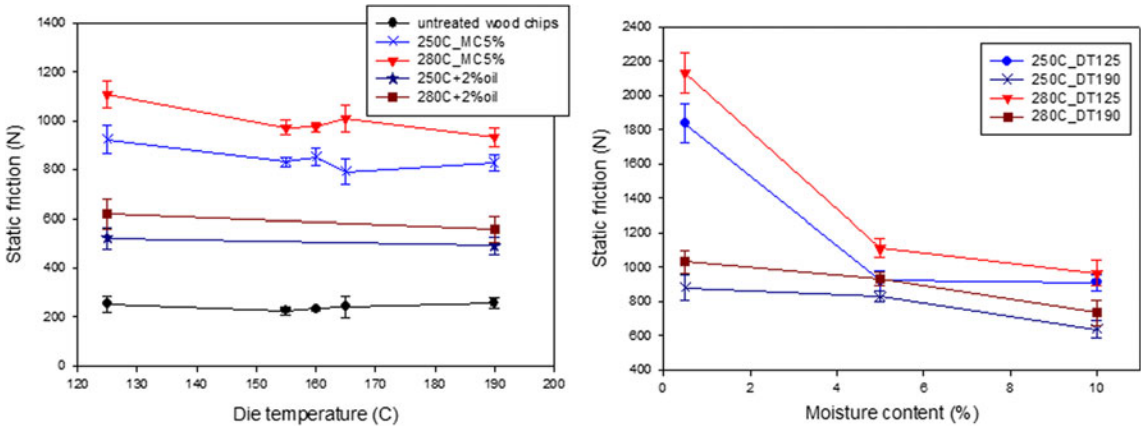

Fig. 5 The static friction in the press channel when pressing out the pellets formed at different die temperatures and with different moisture contents (*MC* denotes moisture content and *DT* refers to die temperature)

difference before and after sieving. The durability value was calculated as the mass fraction of dust free pellets after the treatment in the pellets that was loaded into the tester.

Heating Value

A bomb calorimeter (6300, Parr Instrument Company, USA) was used to determine the higher heating value (HHV, megajoule per kilogram) of pellets produced in the bench-scale pelletizer. Initially, the calorimeter was calibrated using benzoic acid tablets. Samples were prepared by grinding in a commercial coffee grinder (Kenia, Mahlkönig, Germany); 1 g of material was placed in the crucible and fired inside the bomb calorimeter using an ignition wire in the presence of oxygen. The measurements were performed twice.

Grinding Energy

Energy consumption for grinding pellets was determined using a commercial coffee grinder (Kenia, Mahlkönig, Germany) with a screw conveyer feeding system and a disk grinding system. The distance between the two separate disks could be adjusted manually and was set to maximum for all tests. More detailed information refers to [10]. Approximately 200 g of pellets was fed into the feed hopper while the grinder was running. The specific energy required for grinding was determined by integrating the area under the power demand curve for the total time required to grind the sample minus the idling power [17, 18]. Particle size distribution was calculated based on sieve separation of the obtained biomass fraction using a sieve shaker (Retsch, Germany) with nine different sieves (mesh size of 75, 125, 250, 500, 1,000, 1,400, 2,000, 3,150, 5,000 μm). The sieve shaker was run for 40 min and the weight of the individual fractions was determined subsequently.

Results

Single-Pellet Press

The results from the analyses of single-pellets are summarized in Table 1, which shows the experimental settings and the measured pellets' properties. The pellet strength (Fig. 3), pellet density (Fig. 4), and static friction (Fig. 5) data are plotted against die temperature and moisture content of materials prepared at different torrefaction temperatures. It can be seen that the pellets made from untreated wood chips had the highest strength, while the pellets made from torrefied chips with adding 2 % rapeseed oil had the lowest strength. Pellet strength increased when increasing die temperature, and this influence was more pronounced for torrefied materials than untreated wood chips, except for the pellets made with rapeseed oil. The influence of moisture content on the pellet strength was tested on the torrefied materials with two die temperatures. For high die temperature (190 °C), pellet

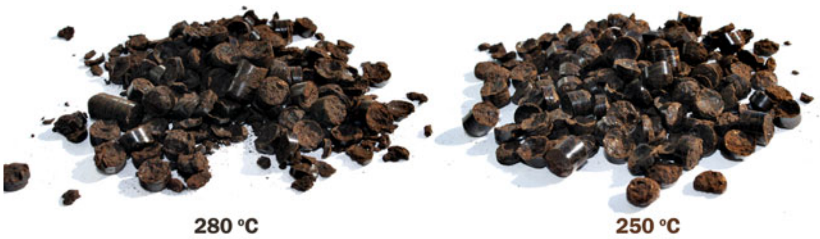

Fig. 6 Picture of torrefied wood pellets produced from pilot-scale pelletizer with 2 % rapeseed oil as lubricant

Table 2 Summary of the results of pellets from pilot-scale pelletizer (95 % confidence intervals of mean values within brackets)

	Moisture (%) [a]	Ash (%) [b]	HHV (MJ kg^{-1})	Durability (%) [a]	Grinding energy (J g^{-1}) [a]
Untreated wood	ca. 10	1.3 (0.01)	19.39 (0.036) [b]	–	–
250 °C+2 % oil	3.5 [c]	1.4 (0.01)	21.95 (0.002) [a]	91.44 (0.26)	3.76 (0.09)
280 °C+2 % oil	3.4 [c]	1.6 (0.01)	22.65 (0.005) [a]	89.91 (1.01)	4.24 (0.12)

[a] As received

[b] Dry basis

[c] After being stored for half year

strength decreased with increasing moisture content, while for low die temperature (125 °C) it seems that medium moisture content (5 %) was preferred. As for pellet density, it increased with die temperature for all tested materials. Similar with pellet strength, medium moisture content was preferred by low die temperature; while for high die temperature, moisture content did not influence the pellet density significantly. This is probably due to water evaporating during pelletizing when die temperature was high. The static friction was measured as the force to make a pellet start to move in the single-pellet press. It is influenced by the sliding friction coefficient, the ratio of compression, and the material-specific parameters, such as the elastic modules and Poisson's ratio [19]. High static friction means higher energy input during pelletizing, lower production capacity, and more heat generated in the press. Figure 5 shows that untreated wood chips had the lowest friction, and materials torrefied at a higher temperature (280 °C) had the highest friction. However, the friction of torrefied material can be reduced by adding rapeseed oil. Furthermore it seems the mean value of the friction decreased a bit when increasing die temperature, but the difference was not statistically significant (Tukey's test, 95 % confidence). The static friction also decreased when increasing moisture content of the material, and the highest reduction happened when increasing moisture content from 0.5 to 5 % for low die temperature (125 °C).

Conclusion can thus be made that pellets made from untreated wood chips had the highest strength, highest density, and the lowest static friction. Pellets made from wood torrefied at lower temperature had lower friction, higher strength and density, when compared to pellets made from wood torrefied at high temperatures. And thus it is preferred for pelletizing. The reason for such difference has been studied by Stelte et al. [11]. It is believed to be due to the thermal degradation of carbohydrates, which results in the reduced amount of available hydrogen bonding sites in the material. By adding rapeseed oil into torrefied wood samples, the static friction can almost be reduced by half. However, pellets made in this way possessed the lowest strength. Increasing the moisture content of the feedstock can reduce the static friction and this may be due to the plasticizing effect of water, lowering the softening temperature of the wood polymers and thus reducing the friction in a hot pellet die [11]. The ability to absorb water decreases with the increase of torrefaction temperature since the number of hydrogen bonding sites decrease with a thermal degradation of hemicellulose, cellulose, and lignin. It is therefore likely that for materials torrefied at high temperatures, most of the added water is adsorbed at the surface and in the pores of the material rather than being bound to the polymers by hydrogen bonding. This will likely reduce the ability of water to act as a plasticizer and its ability to lower the softening

Table 3 Threshold values of the most important pellet physical parameters. More parameters can be found in EN 14961–2 [20]

Poperty	Unit	Enplus-A1	Enplus-A2	EN-B	Testing standard
Diameter	mm		6 or 8		EN 16127
Length	mm		3.15≤L≤40 [a]		EN 16127
Moisture content	w% [b]		≤ 10		EN 14774-1
Ash content	w% [c]	≤ 0.7	≤ 1.5	≤ 3.0	EN 14775 (550 °C)
Mechanical durability	w% [b]	≥ 97.5		≥ 96.5	EN 15210-1
Fines (<3.15 mm)	w% [b]		< 1		EN 15210-1
Net calorific value	MJ kg^{-1} [b]	16.5≤Q≤19	16.3≤Q≤19	16.0≤Q≤19	EN 14918
Bulk density	kg m^{-3}		≥ 600		EN 15103

[a] A maximum of 1 wt% of the pellets may be longer than 40 mm, no pellets >45 mm allowed

[b] As received

[c] Dry basis

temperature of the wood polymers in torrefied wood. Instead of having a positive effect, an excess of water added to torrefied wood might actually have a negative effect on the pelletizing properties. The optimal amount of water to be added to improve the pelletization of torrefied wood is therefore depending on the torrefaction conditions and need to be determined by testing. As for this study, negative influence was found for pellet strength when the moisture content was beyond 5 %.

Bench-Scale Pelletizer

The bench-scale pellet press was used to produce pellets in larger quantity. Wood chips torrefied at 250 and 280 °C were tested. In all tests, it was impossible to get a steady production of pellets of a reasonable quality. The energy consumption of the pellet press was very high (about three times as for untreated wood materials) and close to the maximum of the engine's capacity. The temperature of the die increased very fast and after about 1 h it had reached close to 200 °C where some pellets started to burn right after leaving the pelletizer. Wood pelletizing temperature normally stabilized at a die temperature of 100–120 °C. Tests were conducted with different moisture contents (2–10 %) of the material, but no stable production could be reached and only small batches could be produced before the test had to be stopped. The addition of 2 % rapeseed oil as a lubricant to the torrefied wood materials with a moisture content of about 5 % did improve the production capacity and lower the energy consumption as about 5 kg of pellets was produced for each torrefaction temperature and the die temperature stayed in the range of 130–160 °C, although the pellets were very short compared to the normal pellets (Fig. 6). Pellets made from 250 °C torrefied wood samples had a more uniform length compared to pellets made from 280 °C torrefied wood.

The properties of produced pellets were tested regarding heating value, durability, energy consumption during grinding, etc. Results are shown in Table 2. Pellets made from wood torrefied at a higher temperature had the higher heating value and lower durability, which is in agreement with the pellet strength results from the single-pellet press. The standard pellet properties that required by European Pellet Council is listed in Table 3, ENplus-A1, ENplus-A2, and EN-B stand for three different categories of pellets according to wood types [20]. It can be seen that pellets produced in this study had much higher calorific values and lower moisture contents than the requirements. However, neither of the pellets could reach the durability as required. The length of the pellets seems not to be a big issue according to the standard. Different from expected, pellets pressed from 280 °C torrefied wood consumed more electricity than those pelletized from 250 °C torrefied wood during grinding. The particle size distributions of samples after the grinding energy measurement are shown in Fig. 7. There is almost no difference between the two samples, meaning that pellets made from wood materials torrefied at temperature in the range of 250 and 280 °C have a quite uniform particle size after the grinding.

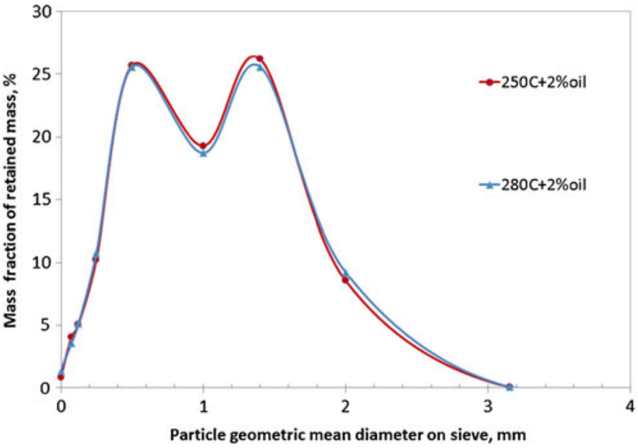

Fig. 7 Particle size distribution analysis of pellets after grinding energy measurement

Conclusion and Discussion

The study has investigated the effects of die temperature, moisture content, additive, and degree of torrefaction on properties of pellets produced in a single-pellet press, i.e., pellet density, static friction between pellet surface and the press channel, and pellet strength under compression. Single-pellet press tests showed that pellets made from torrefied wood materials do not achieve the same strength and density as untreated wood pellets. It has also been observed that higher die temperature, medium moisture content (5 %), and lower torrefaction temperature were preferred when pelletizing torrefied wood samples. Furthermore, negative influence was found for pellet strength when the moisture content was beyond 5 %. Therefore, the optimal amount of water to be added to improve the pelletization of torrefied wood is suggested to be depending on the torrefaction conditions and need to be determined by testing.

On the other hand, performing tests in a bench-scale pelletizer showed that pelletizing torrefied wood suffered from high energy consumption and heat generation in the press channel causing pellet self-ignition. This is in agreement with the higher static friction found in the single-pellet press for torrefied materials. As the static friction decreased a lot by adding 2 % rapeseed oil as a lubricant, this additive was also tested in the bench-scale pelletizer with wood torrefied at both 250 and 280 °C. Production capacity was improved and relatively stable operation was achieved. Static friction appears to be the key factor to consider when scaling up the pelletization of torrefied wood samples. Tuning moisture content or die temperature did not ease the production in a bench-scale pelletizer significantly, and high die temperature (190 °C) can easily cause a fire hazard.

Although the produced pellets were short and the durability could not reach the requirement for pellets in the market, the advantages of pelletizing torrefied wood are that heating value was increased on mass basis and a uniform particle size distribution was observed after the grinding. These could be beneficial for co-firing torrefied pellets with coals in power plants. In fact, a variety of pellets made from torrefied biomass are available in markets and they possess good durability, which means the pellet quality can still be enhanced by adjusting the torrefaction conditions, finding the proper additives or a pelletizer with more suitable operating characteristics. The bench-scale pelletizing tests presented in this paper is a very preliminary study mainly for pellet quality investigation. It turns out that there is a gap between parameter study using a single-pellet press and the operation in a real pelletizer. The optimized pelletization conditions regarding the pellet properties from a single press may not work for the bench-scale pelletizer. First, the recommendation of high die temperature (>200 °C) made from single-pellet press [21] should be used with caution. Second, the static friction appears to be the crucial parameter linking to the real production. However, the factors influencing the stable operation of the pelletizer should be further investigated.

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